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Technical and economic assessment for the production of torrefied ligno-cellulosic biomass pellets in the US

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ABSTRACT

Manufacturing and trade of wood pellets in the United States (US) has seen an exponential growth in the last few years, triggered by its potential utilization in applications typically dominated by fossil fuels, such as heat, power, and combined cycle generation. This combination holds the promise of delivering a high density, high heat value fuel, making it a better substitute for coal and other fossil fuels. This combined process exists only at pilot-plant levels. Scale-up of the technology and feasibility of such projects remain largely unexplored. This research developed a techno-economic model for the production of torrefied wood pellets, considering critical production parameters, and evaluating sensitivity to changes in CAPEX (Capital Expenditure), biomass delivered costs, labor, and energy consumption of a facility, evaluated through a case-study. Results indicated that biomass delivered costs and depreciation are the most significant factors influencing production with CAPEX being the most sensitive variable due to high investments in torrefaction reactors. The selection of different torrefaction technologies, and adequate binders, may represent a major improvement in the feasibility of a project by reducing capital costs drastically. Back-calculated price for torrefied wood pellets is $261/metric ton (100,000 metric tons/year facility), and delivered price may reach $282/metric ton, a similar cost compared to regular pellets. Preliminary analysis of carbon credits as additional income may considerably increase the likeability of the business, and further enhance profitability.

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1. Introduction

The resurging interest in biofuels has produced a large amount of research and development in new technologies and reevaluation of old technologies. Among these technologies, torrefaction has been identified as one of the most promising pre-treatments [1] to improve the performance of biomass based fuels.

Traditional biofuels industries such as wood pellets have seen a renewed interest and an exponential market growth [2,3] in recent years. Most of this market growth is due to government mandates. Even with moderate projections (10% demand increase annually), 10–12% of all harvested wood in the world would be destined to end up as wood pellets by 2025 [4], and global markets are expected to double in 2014 (11.3 million metric tons in 2008 vs. 22 million metric tons by 2014 [5]). Part of the industry's success relies on using proven technology [6], making its expansion relatively easy, with only the occasional problems typical of growing industries. [7].

Torrefaction of ligno-cellulosic biomass has been extensively investigated in the literature [8–13]. It is described as a thermo-chemical process that degrades hydrophilic polysaccharides and hydroxyl radicals, producing an increase in the percentage of lignin on a dry weight basis, thereby reducing the hydroscopicity of the material and increasing energy density.

Wood pellets have also been broadly documented in previous literature. During pelletization the biomass is milled, dried and mechanically densified, enhancing its heating value and burning characteristics [3,7,14,15]. Previous research proved the feasibility of producing torrefied pellets from ligno-cellulosic biomass [6,16,17], demonstrating improved properties such as heating value, bulk density, and grindability vs. wood chips, pelletization, or torrefaction on its own.

A large part of the market growth of pelletized woody material has been intended to supplement or replace coal for power generation. Studies indicate that torrefied wood's energy content per kilogram are similar to that of coal, and 12–41% greater than that of wood pellets depending on the degree of torrefaction [18]. The disadvantage of wood vs. coal is its lower bulk density (641–721 kg/m^3 vs. 897–993 kg/m^3 for coal). The addition of pelletization to torrefaction would potentially create a bio-based fuel with similar energy density to coal, prompting the adoption of this product for replacing coal in heat and power facilities. Recent studies aim in the direction of making a combined torrefaction–pelletization process possible in a commercial scale [4,6]. The Energy

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Research Centre Netherlands (ECN [19]) developed a production process for torrefied pellets [6], while Andritz developed a brand-named process with similar unit operations and principles as the ECN process [20]. Both processes are said to provide pellets with better hydrophobic properties, higher density, and similar strength characteristics as non-torrefied pellets.

Mitchell et al. [21] evaluated the business case for torrefied wood pellets, describing that torrefied pellets may have twice the energy bulk density as wood pellets, with the potential of being highly competitive. Uslu et al. [22] confirmed that merging torrefaction and pelletization reduced transportation and handling costs. Van der Stelt et al. [1] found three potential applications for torrefied wood pellets; entrained flow gasification, small scale combustion using pellets, and co-firing in pulverized coal fired power stations. Gasification is still a technology under development for commercial applications, while co-firing in power plants is a concept that has been evaluated by the authors in a previous publication [23].

Despite the vast research efforts of integrating torrefaction and pelletization to produce a pelletized fuel, only one aspect has been considered in a limited scope up to date: its technical and economic evaluation for full scale production in the US. Uncertainty exists in large scale production costs, durability, and the necessity of external binding agents.

The objective of this research is to develop a technical and economic assessment that allows evaluating the feasibility of torrefied wood pellets production in the United States; a case study for a 100,000 metric tons/year facility is utilized to describe and evaluate the results of such model. A second objective of the research is the identification of potential binders for torrefied pellets production, and the determination of its influence on the economics and technical characteristics in a torrefaction–pelletization project.

2. Methods

The present model was developed with a similar concept as previous work performed by the authors [3,23–28]. The analysis of a completely integrated torrefaction–pelletization process involves the identification and assessment of variables in three areas: (1) Mass balance which accounts for biomass weight and energy consumption, (2) the type of fuel used in the production process and the associated energy costs, and (3) a financial section, integrating the main variables (biomass delivered costs, capital expenditure, depreciation, labor, operating, and miscellaneous) into indicators that allow evaluating profitability of torrefied wood pellets production (Internal Rates of Return (IRR), Net Present Value (NPV), and sensitivity analysis).

The model allows user-friendly inputs of costs and production related variables to evaluate scenarios and different production conditions. Table 1 summarizes the user-modified variables in the model.

Torrefaction level represents a critical variable for determining the product properties and quality, and is defined by the residence time and temperature of operation inside the reactor [13,29]. These two parameters determine the changes in the levels of cellulose, hemicellulose, and lignin, as well as the amount of VOC's (Volatile Organic Compounds) available for combustion. A wide range of torrefaction temperatures and residence times have been reported in the literature, varying between 1 and 40 min, and from 200–400 °C. Experimental information from a torrefaction machine (screw-type reactor) in operation at North Carolina State University, and previously described by the authors [13], allowed to establish three torrefaction levels in the model. These levels influence the final moisture content, binder requirements, and High Heating Value (HHV) of the product. Light torrefaction was established at 3 min residence time, and 280 °C with a resultant HHV of 19.7 MJ/kg (8458 Btus/lb.); medium torrefaction is defined as 4 min residence time at 350 °C with a resultant HHV of 21.1 MJ/kg (9060 Btus/lb.), and dark torrefaction is defined as 6 min residence time at 400 °C with a resultant HHV of 22.1 MJ/kg (9502 Btus/lb.).

In order to estimate the profitability of torrefied wood pellets production, the process design and unit operations have to be properly identified. Fig. 1 presents the schematics of a proposed process for torrefied pellets production, from delivered biomass to final storage of torrefied pellets at the facility's gate, assuming that biomass is debarked by wheeled forestry debarkers (cost of debarking included in biomass delivery as debarked roundwood).

2.1. Process description

The process flow in Fig. 1 is modified from previous investigations on torrefaction–pelletization as pretreatment, with the addition of a mixing or conditioning process, for the inclusion of a binding agent to aid in pellets formation and durability, as well as a hammermilling process for further particle size reduction. This is allocated after particle cooling in the torrefaction unit. The model considers biomass received in an open-space storage area, and product is considered to be stored in a naturally ventilated warehouse area.

A torrefaction unit is capable of producing 80–100% of the necessary heat to pre-dry the biomass entering the reactor and during torrefaction [13,30], by combusting the VOC's released, removing the majority of moisture present in the biomass at the time of processing. In this model torrefaction is assumed to be an autothermal operation; a process that takes place without the addition of external heat except for initial ignition. The model proposed accounts for a thorough analysis of the torrefaction unit, calculating a detailed mass and energy balance. One of the most important energy balance factors is represented in the torrefaction unit, in which water is evaporated, a pilot flame of propane is kept, and the energy density of the biomass is increased. Ten percent of the original energy is lost in the process. Fig. 2 shows a schematic of the energy balance.

Biomass entering the unit is considered at 45% moisture content; an average 10.5 MJ/kg heating value for wood is considered (wet weight basis), and VOC's extracted from the biomass are recirculated and burned in a combustion chamber along with the propane. This type of mass balance is the minimum required for the autothermal operation of the unit. Fig. 3 shows the detail (mass circulation) of the torrefaction unit.

Previous studies indicate that torrefaction is performed in five main stages: initial heating, pre-drying, post-drying, torrefaction, and solids cooling [1]. The stage of pre-drying is performed between 100 °C and 200 °C, eliminating the need for a separate drying unit in the process. In addition, due to high operation temperatures, biomass exiting the reactor requires cooling of the material prior to pelletization. The task is accomplished by utilizing a counterflow cooler after torrefaction. It operates by the circulation of fresh air through the product. It discharges the product only once the required temperature set by the operator has been reached.

Three different types of feed mechanisms for the torrefier can be selected in the model: screw reactor, rotating drum, and moving-bed. Based on the recommendations of Bergman [6] four separate production lines with same conditions are utilized in the model. The hammermilling process is allocated after torrefaction in order to minimize power consumption [31]. Conditioning or binder addition to the biomass is performed due to the non-fibrous properties of the torrefied material in order to improve quality on the pelletization process [13].

Table 1
User-modified variables utilized in the model.

Type	Variable
Production variables	Torrefaction level (light, medium, dark)
	Moisture content of biomass (%)
	Working hours/year (h/yr.)
	Biomass type/form (chips or roundwood)
	Binder selection (steam, feed corn, soybeans, DDG)
	Mass losses (per unit operation) (% w/w)
	Efficiency (per machine) (%)
	Production level (annual) (metric tons/year)
	Binder requirements (%w/w)
Cost variables	Biomass delivered Costs ($ metric ton)
	Torrefaction Technology (screw, drum, fluidized bed)
	Binder costs ($/metric ton)
	Plant location (state in the US)
	Energy costs ($/kW h)
	Carbon credits ($/ton CO_2 displaced)
	Capital costs ($)
	Discount rate (%)
	Internal rate of return (%)
	Labor costs ($/year)
	Cost of consumables ($/unit and $/metric ton)

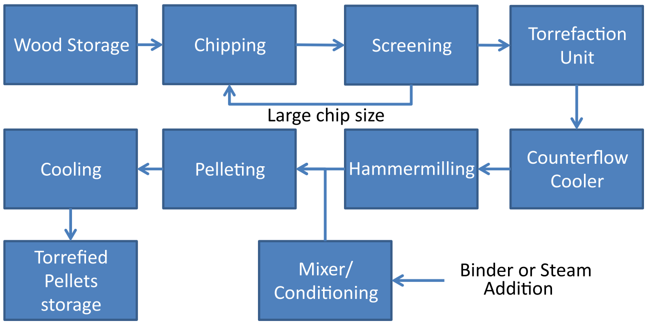


Fig. 1. Torrefaction–pelletization process for an industrial-scale factory.

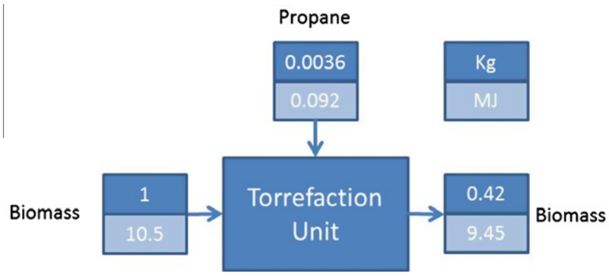


Fig. 2. Mass and energy balance for the torrefaction unit, including pre-drying.

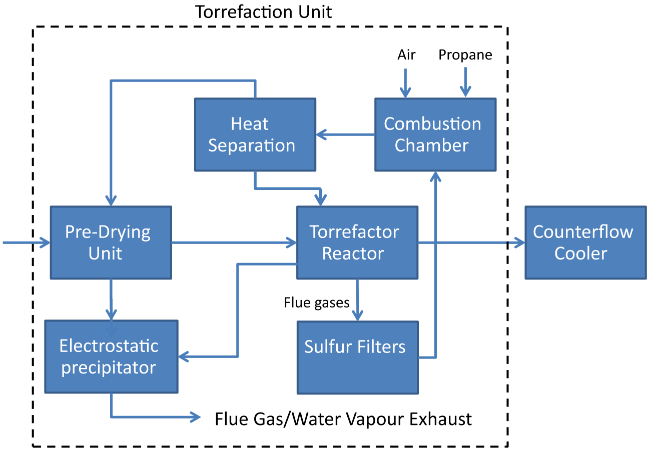


Fig. 3. Schematics of the proposed torrefaction unit, including pre-drying.

2.2. Mass balance

The model developed calculates biomass requirements of the factory based on annual production (product output), biomass moisture content, torrefaction conditions (level), and biomass losses throughout each unit operation, giving a biomass throughput for each separate process. Information from previous literature was used to estimate flue gases, water vapor release, and fuel requirements for the torrefaction unit [56–58]. No mass losses are considered in subsequent unit operations, although these can be user-modified. Based on experimental information from the torrefaction unit at North Carolina State University, a propane pilot flame is used in the combustion chamber, at a 2% weight rate of the total gases entering the chamber. Although the torrefaction process can run without the addition of external heat sources in autothermal operation, the addition of the pilot flame ensures proper combustion, uniform heat flux and flow of gases, as well as maintain torrefaction temperatures, product quality, and uniformity. Calculations of the propane requirements are also included in the mass balance. Future work may consider the utilization of natural gas, which may deliver lower costs per unit of heat transferred.

The addition of a binder to the feedstock prior to pelletization has many different formulations. Adapa et al. [59] studied biomass steam conditioning prior to pelletizing, suggesting a 25% weight-basis steam addition to the biomass (conditioning value utilized as a baseline in the model), while Tijmensen et al. [60] suggested ratios of 19%, 34% and 60% steam addition in various gasification processes, being 34% the ratio most commonly used (in kg steam/kg biomass input). Suggested ratios of DDG's and other grains to pellet production are 85% wood with 15% grains [33], and 12:1 ratio of wood to soybeans (approximately 8% weight, dry basis [61]). This information is included in the model. Results and binder addition ratio in the mass balance are automatically modified when selecting a particular type of binder.

2.3. Energy utilization

The electrical energy consumption of the machinery (kW h/year) is calculated based on the work of Digiacomo and Taglieri [62], Pirraglia et al. [3], and Bergman and Kiel [56]. In this evaluation, the average power consumption of each process, operating at a 100% capacity based on the production requirements of the facility, is considered. The mechanical systems of the torrefaction reactor, such as fans, blowers, and valves, are considered part of the miscellaneous equipment in the electrical energy calculations. Additional propane burned in the combustion chamber is provided in case that conditioning of the biomass is required (for steam generation in the boiler, only required in conditioning). Considering the average energy consumption of the machines, the plant location of the facility (for energy costs effect), and the working hours per year, the model calculates total yearly energy consumption of the factory, and average energy consumption per metric ton of torrefied pellets produced. Fig. 4 presents the percentage of energy (electrical) consumption of each unit operation in the torrefied-pellets process, as well as the kW h of energy consumption per metric ton of torrefied pellets produced for each process.

The most significant energy consumption process is represented by pelletization, with the miscellaneous equipment of the facility being second in importance. If conditioning is required, significant steam generation costs (with propane) may be reached. Steam addition costs widely vary depending on production rates, annual operating hours per year, boiler efficiencies, and type of fuel utilized to produce the steam. Considering propane and heat exchanging from the off-gases in the torrefaction process as fuel for steam generation, steam costs are calculated according to the following parameters (Table 2).

Considering the parameters previously mentioned, and utilizing a Clever Brooks Boiler Steam Costs Calculator [63], along with propane technical tables from Alternate Energy Systems, Inc. [64], average steam costs account for $78.64/metric ton of steam produced. More detail in the calculation of other binders is provided in the next section.

A critical energy element in the process is presented in the torrefaction unit. In order for the process to be efficient, the energy for pre-drying the biomass, and perform the torrefaction reaction in the unit must be self-generated. In the unit operating at North Carolina State University, it is estimated that 80% of the necessary heat for pre-drying and torrefaction is generated by combusting the off-gases of the biomass entering the process, and the remaining 20% of the required heat is generated through a propane flame that ensures not only that the required heat needs are met, but also ensure proper combustion of the gases in the chamber, uniformity of the product, and aids during start-up of the machine. Because of this. the utilization of a propane flame in the unit is justified to generate the 20% additional energy required.

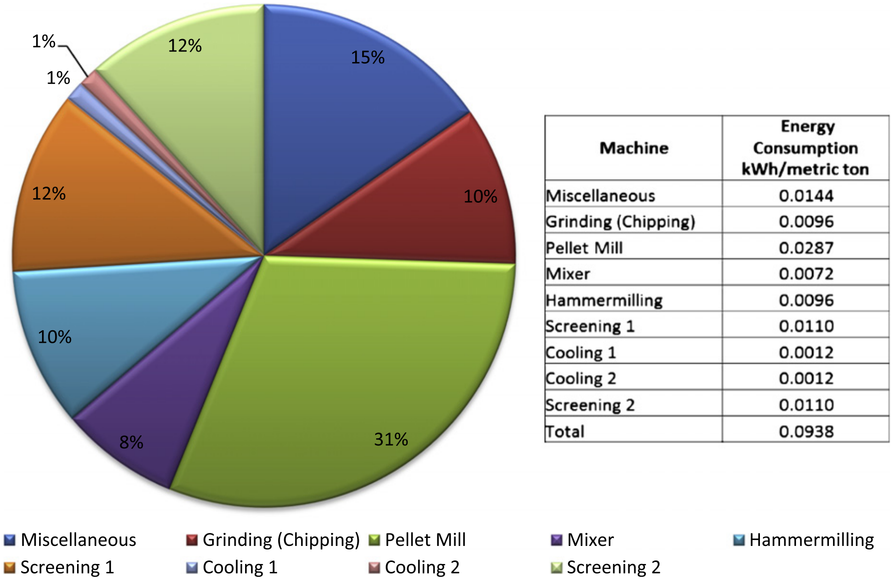
Under autothermal conditions (previously described in the Methods section), and depending on the biomass source, the torrefaction off-gases that contribute to most of the heat generated in the combustion chamber are formaldehyde/acetaldehyde, methanol, pyruvaldehyde/propanal-2-one, furfural, furfuralalcohol, and coniferyl alcohol, among other product gases [65]. They generate the aforementioned 80% of the heat process (torrefaction and pre-drying).

2.4. Economic parameters

This section contains detailed information on CAPEX of buildings and machinery, engineering, labor, energy, consumables, and biomass costs. The equipment costs, capacities, and engineering costs were obtained directly from manufacturers (in the case of boiler, grinders, screeners, counterflow coolers, hammermills, pellets mills, conditioners, and mixers). Costs of installation, siting, engineering, maintenance, and miscellaneous equipment, along with miscellaneous costs related to the boiler (costs of accessories: feedwater pumps, fans, fuel heaters, steam for fuel atomizers and soot blowing, treatment chemicals, and environmental and maintenance costs) are retrieved from recent literature [3,66,67]. The values obtained from previous literature were adapted to 2011 values using the CWCCIS (Civil Works Construction Cost Index System) conversion index.

Since torrefaction of biomass in large scale is a recent concept; there is still a lack of reliable sources for cost estimates. Suppliers of this type of equipment are scarce, and the majority is still in the pilot test stage for their technologies. Some authors indicate that capital costs of torrefaction are mainly dominated by the cost of the reactor [68,69]. Some authors have estimated the capital costs of torrefaction units per metric ton of biomass required per hour (capacity of the equipment), and depending on the type of technology implemented. The work performed by Bergman et al. [19,56,68] is of great importance. Although this work is performed under European market conditions, it provides with one of the few complete and detailed estimates for torrefaction costs, including engineering & supervision, installation and construction costs. In their studies, three types of technologies, with their associated capital cost, are described (and therefore, utilized in this project): screw reactor, with $32.72/metric ton (€22/metric ton) costs, rotating drum with $23.80/metric ton (€16/metric ton) costs, and moving bed, with $11/metric ton (€11/metric ton); these estimates were developed under the assumption of a 200,000 metric tons/year factory. In the present project, these cost estimates are utilized, and are adjusted to $/metric ton using the average conversion rate of €/$ of 2005, and the CWCCIS index to convert it to 2011 dollar values. In the model, the three types of technologies included can be modified by the user, automatically adjusting production parameters and capital costs.

For equipment other than the torrefaction unit, capital costs depend on the equipment capacity, and are adjusted (depending on annual production as input) utilizing the power law rule [70] which estates that: $Inv = Inv_L \times (P/P_L)^{0.7}$; were Inv represents capital investment depending on plant size(metric tons/h), Inv_L represents capital investment of original equipment, and P and P_L



Machine	Energy Consumption kWh/metric ton
Miscellaneous	0.0144
Grinding (Chipping)	0.0096
Pellet Mill	0.0287
Mixer	0.0072
Hammermilling	0.0096
Screening 1	0.0110
Cooling 1	0.0012
Cooling 2	0.0012
Screening 2	0.0110
Total	0.0938

Fig. 4. Energy consumption in the factory by process, estimated for a 100,000 metric tons/year facility, with an approximate energy consumption of 0.094 kW h/metric ton of torrefied pellets. Torrefactor mechanical systems are considered part of miscellaneous equipment.

Table 2
Characteristics considered for steam costs calculations.

Feedwater temperature	24 °C
Type of fuel	Propane
Fuel costs	\$0.36/l (\$1.346/gallon)
Efficiency	85.70%
Annual hours operating*	8400
Operating pressure	1135.54 kPa. (150 psig)
Boiler horsepower	255 BHP

Table 3
Parameters utilized in the case study factory.

Parameter	Value
Annual production	100,000 metric tons/year
Required raw material (green)	230,956 metric tons/year
Initial moisture content	45%
Final moisture content	7% ± 1%
Heating value of product	19.673 kJ/kg (8458 Btu/Lb.)
Torrefaction level	Light torrefaction
Type of binding treatment	Steam conditioning
Binder added (%w/w)	25%
Carbon credits	\$0/ Metric ton

represent the capacity required on the equipment, and the capacity of the original equipment respectively. 0.7 represents the scaling factor, following recommended values by Andersson et al. [71].

In addition to basic capital costs, the model adds indirect and contingency costs, calculated as 24% and 10% of the total capital cost of equipment respectively [72]. Biomass storage after pelletization, with warehousing costs and space represents 7.6% of total plant building [66]. This warehouse space is considered assuming that torrefied pellets are directly dumped into transport trucks, with a bulk-delivery logistics strategy. With all capital costs information, plant and equipment depreciation is calculated in the model using a MACRS-7 method (Modified Accelerated Cost Recovery System, in 7-year class, which depreciates 14.29%, 24.49%, 17.49%, 12.49%, 8.93%, 8.92%, 8.93%, and 4.46% each year from the total assets value in 7 years), with a capital expenditure schedule of 20%, 40% and 40% in 3 years.

Labor costs, headcount, and structure are calculated based on the average wages provided by the Bureau of Labor Statistics [73], and by previous literature [3,67,69]. The model calculates, based on this information, the annual direct and indirect labor costs, adjusted depending on the annual facility production, number of shifts per day, and number of working hours per year.

Biomass delivered costs are fixed at \$45/bone dry (metric) ton (BDT), considering an annual cost increase of 1%. This value is lower than previously reported delivered costs [3,24]; in order to be consistent with more recent delivered costs reported [74]. Changes in biomass delivered costs can be performed in the model, allowing for sensitivity analysis. The final product is intended for bulk delivery, reducing the handling, packaging, and consumables utilization in the facility, this differs from previous reports on wood pellet facilities [3]. Consumables are considered as plant and office tools (\$80,000/year), lubricants, rollers and dies for pelletizers (\$3/metric ton), as well as spare parts for the torrefactor and other equipment (\$3/metric ton). Additional costs are segmented in marketing/sales fees (\$6/metric ton), maintenance and repairs (\$8.85/metric ton), forklift and front-end loaders costs (\$0.17/metric ton). Values for each estimate are taken from Campbell [67], and Bergman et al. [68].

The addition of a binder represents an additional cost that must be taken into consideration. The model can adjust the type of binder used, with four different choices: feed corn, DDG's, soybeans, and steam. Conditioning by steam added to the biomass seems more adequate for mild torrefaction treatments; as it is the default option when light torrefaction is selected in the model. As previously mentioned, the cost of steam for the facility, considering a 34% weight–weight addition of steam to biomass, is \$78.64/metric ton of steam.

For every other torrefaction treatment selected in the model (medium and/or dark torrefaction), binding agents processed by mixing appear to be more adequate. The model automatically adjusts the percentage weight–weight of binder, depending on the user's selection also adjusting current costs per metric ton of binder added. Latest information on binders costs reports the following: soybean prices have fluctuated between \$420.05/metric ton and \$509.93/metric ton during 2011 (commodity price [75]), with an average of \$480.98/metric ton, DDG's prices are currently at \$201.7/metric ton (national average [76]), and feed corn average 2011 prices (commodity) was \$156.02/metric ton [77]. These costs are calculated in the model and added to the financial section (income statement). In the results and discussion section, a case study for the model is presented, assuming a factory producing 100,000 metric tons/year of torrefied wood pellets.

For the proposed case study, and in a similar structure as previously described by Pirraglia et al. [3], the parameters considered are summarized in Table 3; this case study considers no carbon credits.

3. Results and discussion

Other studies have analyzed size factories similar to the one proposed in this case study, such as Topell Energy [58], a 200,000 metric tons/year plant described by Björklund [78] utilizing a screw reactor technology, Mitchell et al. [21] which described an 80,000 metric tons/year facility. While some of these studies concluded that prices for torrefied biomass are still not viable, they also state the need for more technical demonstration and accurate estimates [78], especially since many of these studies provide scarce information about the economics, dimensions, calculations, and assumptions of the ventures; In this section of the study, the authors intend to cover many of these aspects.

3.1. Energy usage

The case-study factory considers the average electricity and propane costs (\$/kW h and \$/L) for the US, updated to January 2012. In the model, plant location can be modified to any state, and local and regional electricity and propane costs will be automatically adjusted, following the information collected from the U.S. Energy Information Administration on electricity and propane costs [79,80]. For energy calculations, it is assumed a screw reactor technology for the torrefaction unit, operating in the autothermal range, with miscellaneous mechanical equipment of the torrefier running on electrical power, and a steam boiler also running on propane. For sensitivity analyses, other torrefaction technologies, and different binder that do not require boilers running on propane, are considered. Table 4 shows the results for energy consumption and costs in the case study.

Energy costs present a reduction if compared with other alternatives of biomass pre-treatment such as wood pellets. Compared

Table 4
Electrical and propane usage and costs for the case-study factory.

Propane usage (l/year)	818220.15
Propane Cost (\$/l wholesale)	0.36
Total propane costs	**290,940**
Electricity usage (kW h/year)	2334
Electricity cost (\$/metric ton)	13.35
Total electrical costs (\$/year)	**1334,760**

to the work by Pirraglia et al. [3] on a 75,000 metric tons/year wood pellets facility, reductions in total energy consumption are close to 43%, even considering that the size of the facility in the present study is 25% larger in metric tons per year manufactured. This indicates that energy consumption of this combined pre-processing might present a competitive advantage over the highest energy consuming pre-treatment (wood pellets). This characteristic is due to the absence of a separate drying process; although other equipment increases the energy consumption of the facility, most of this energy is typically used in drying biomass, a process that is eliminated by the autothermal operation and excess heat generated by the torrefaction unit.

In addition, the evaluation of boiler, and combustion chamber requirements and costs to switch from a traditional burning fuel such as propane, to biomass burning from the same delivered biomass for pellets production, or from rejects and biomass waste, is a topic that needs further evaluation for its potential to reduce energy costs of the facility.

3.2. Cost structure

In the present study, four parallel lines of torrefied material are assumed before pelletization, as recommended by Bergman et al. [68]. For CAPEX (Capital Expenditure, expenditures that will benefit the business in the future, such as equipment) effects, this influences the selection and number of feeding systems, conveyors, and miscellaneous equipment, having a fixed value, with a difference in capacities if production levels are changed (increased and/or decreased). Based on the automatic calculations of the model (mass balance section), and the annual production set as 100,000 metric tons/year, the factory must process 11.9 metric tons/hour of torrefied wood pellets, with different levels of biomass being processed at each stage. Based on these requirements, and using the estimates by Bergman et al. [68] on torrefaction costs per metric ton produced for a screw reactor (€22/metric ton), CAPEX of the torrefaction unit and the rest of the equipment was developed, considering the average euro-dollar exchange rate of 2005, and a CWCCIS index to extrapolate costs to 2011 values. Detailed CAPEX calculations are provided in Table 5.

The cost of the torrefaction unit represents the major CAPEX element (43% of the total installed costs). Notice that according to the estimates provided by Bergman et al. [68], engineering and installation costs are included in the reported value of €22/metric ton for the torrefaction unit. The high percentage that torrefaction represents in the capital costs is said to be typical of a new technology, or a "first-plant" cost, and subsequent facilities can see capital costs reduced by as much as 20% for every doubling in their number [69].

Direct and indirect labor total 33 employees and administrative personnel. The factory considers three 8-h shifts per day. This information is part of the operating costs of the factory, along with consumables, binders, and additional costs. Since the binding agent considered for the case study is steam, the annual estimated cost of steam is reported. A summary of operating costs is presented in Table 6.

The labor structure proposed in the model considers one supervisor, four production employees, one forklift operator, one maintenance technician, and one raw material employee as direct labor. Administrative (indirect) personnel is structured with two accountants, two sales/marketing representatives, one executive/administrative assistant, one finance manager, and one general manager. With all the costs included in the model and dependent on the inputs, total production costs for the facility can be calculated, considering also depreciation as part of the production costs. Fig. 5 shows the main production costs categories and its influence in the total production cost of torrefied wood pellets.

Biomass delivered cost (established at $45/metric ton) represents the largest production cost, accounting for 29%. Depreciation is also an important factor (25%), being close to biomass delivered cost, and greatly influenced by the torrefaction unit. However, it is substantial the percentage that binders (in this case steam) represent in the overall production costs (13%), being more significant

Table 5
CAPEX for the case-study factory.

Item	Number required	Cost per each equipment (US $)	Installation cost (US $)	Total equipment costs (US $)	Total installation costs (US $)	Total equipment + installation costs (US $)
Misc. conveyors	8	15,188	7594	121,508	60,754	182,262
Front-end loaders	2	22,783	–	45,566	–	45,566
Feed hopper	20	7594	4557	151,880	91,140	243,020
Grinder	4	174,935	113,914	174,935	455,654	630,589
Torrefaction unit	4	7078,686	–	28,314,745	–	28,314,745
Live bottom bin	20	18,226	15,188	364,523	303,769	668,293
Continuous dual-shaft biomass mixer	2	480,000	216,000	960,000	432,000	1392,000
Hammer mill	2	83,536.61	37,971	167,073	75,942	243,016
Pellet mills(s) (including conditioning)	2	265,798	83,536	531,597	167,073	698,670
Boiler/water heater (255 BHP)	1	167,073	1670	167,073	1671	168,744
Counterflow cooler 1	4	227,827	18,226	911,308	72,905	984,213
Counterflow cooler 2	4	227,827	18,226	911,308	72,905	984,213
Screener 1	4	15,188	12,151	60,754	48,603	109,357
Screener 2	4	15,188	12,151	60,754	48,603	109,357
Fork lift	2	22,783	–	45,565	–	45,565
Site and site preparation	1	156,000	–	156,000	–	156,000
Paving/receiving station/load area	1	60,000	–	60,000	–	60,000
Building and office space	1	1020,000	–	1020,000	–	1020,000
Misc. conveyors	8	15,188	7594	121,508	60,754	182,262
Total				**34,346,097**	**1891,773**	**36,237,870**
Storage warehouse						77,622
Indirect costs (24%)						8671,975
Contingency (10%)						4480,520
Total installed costs						**49,467,987**

Table 6
Operating costs for the case-study factory.

Operating cost	$/year
Direct labor	1274,765
Indirect labor	697,829
Consumables	1465,714
Additional costs	1502,043
Binding agent (steam conditioning)	2673,760
Total operating costs ($/year)	**7614,111**

than labor costs (10%) and energy costs (8%), and implying that selection and procurement of the adequate binder have an important effect in the overall production costs.

3.3. Binders

Binders in pellets are used to improve binding, lubrication, combustion properties, and abrasion characteristics [32], by forming a bridge, film, matrix, or chemical reaction that strengthens interparticle bonding [33]. In the manufacturing of regular wood pellets (without any pre-treatment), the lignin present in the wood acts as glue for the cellulose fibers [34] allowing pelletization without the addition of binders, and depending on fiber characteristics [35,36]. Lignin thermosetting properties are activated at temperatures higher than 140 °C, acting as a resin [37]. Under normal pellet plant operating conditions, with 8–15% moisture content of the feedstock this temperature is reduced to 100–135 °C. When strength, durability or heating value properties are not properly reached, the addition of binders become necessary to increase pellet quality [38]. During torrefaction, lignin undergoes loss of properties with temperatures above 270 °C [6,19] reducing the possibility of its utilization as binding agent, making large-scale production of torrefied pellets difficult without adding external binders. Thus, several different options of binders were investigated and considered for this research, since binders will affect mass balance, energy balance, capital costs (addition of a mixer and/or conditioning unit), and production cost per metric ton of torrefied pellets.

Bergman et al. [19] and Mani [39] proposed the addition of steam to increase moisture content before pelletization, thus softening the lignin and aiding in the binding of the pellets. According to Kallio [33], steam conditioning is essential to provide heat and moisture to activate inherent binders of the biomass. This type of binder may give adequate results if lignin has not undertaken heavy denaturation, being ideal for "light" or mild torrefaction temperatures.

Tumuluru et al. [34] reported the suitability of different types of binders and its influence in pellet quality. In this work, starch and protein binders have better properties for pellet quality. Starch acts as a binding and lubricant agent, easing the material flow through the die, while protein based binders improve binding capacity [40,41], increasing pellet durability [42,43]. Binders with combined proteins and starch content may have a more significant influence on densification and quality of pelletized biomass, producing denser and more stable pellets [44,45]. Mani [39] proposed the addition of starch-based binders, bio-oil, black liquor and/or lignin to torrefied material in order to form durable pellets. For large production volumes, availability of bio-oil, black liquor, or lignin may be limited. Thus, a binder that can be procured in large quantities and with well-established supplies must be selected to reduce costs and resources used.

Several binders have been evaluated in previous literature [38,46,47]. Kallio [33] reports that small amounts of starch (2% weight/weight) increases pellet (you only need to say pellet, because you are talking about many pellets) durability; Nikolaisen et al. [48] reported the use of 2–5% (weight/weight) molasses as binding agent, while Wilen et al. [49] used kaolin (3% weight/weight). Rapeoil [48] and pineoil [50], has also been evaluated, but results indicate that addition of fats/oils reduce pellet durability. Researchers and companies must keep in mind that certain markets may limit the utilization of some binders. Austria allows only 2% (weight/weight) binders addition rich in starch content (e.g., maize [32]), while Germany allows only molasses, natural paraffin or starch [51].

Soybeans represent a great candidate, providing considerable amounts of protein, starch and oil that may act as binder and lubricant, with a composition of 38% protein, 30% soluble and insoluble carbohydrates, 18% oil, and 14% moisture, ash and others [52]. In addition, its procurement in the United States is relatively easy, since the US represents the largest soybean producer [53] with 35% of world production.

Corn is also another excellent binder, composed of 72% starch, 10% cellulose and hemicellulose, 9% protein, and 8% oil and other components [54], and is the most widely produced grain in the country, with 37% of the planted crop land being corn. Corn is currently being heavily utilized in the production of ethanol and as a food crop, so it is recommended the utilization of feed corn be used. In effect, corn for feed represents an optimal binder, which does not adversely affect the food production industry.

DDG's (Distillers Dried Grains) composition makes it also an adequate candidate for binding agent. DDG's are typically by-products of the distillery industries. DDGs' typical composition is made up of 31% protein, 10% fat, 4% starch, and 55% cellulose/hemicellulose [54]. The United States has a median estimated production of 39.7 million metric tons/year of DDG for 2012 [55], making it a readily available binder for the densified fuels industry.

In the present study, the authors include the previous mentioned options of binders for the model, steam (for conditioning of lightly torrefied biomass), feed corn, DDG, and soybeans. The evaluation of each binder influences the selection of further machinery (mixer or conditioner), capital costs, production costs, and mass balance of the process. Detailed information about binder ratios, costs, and addition in the model is provided in further paragraphs. It is necessary to highlight the lack of information and available tests results regarding percentages, types, and use of binders for torrefaction, and the influence in product characteristics, economics, and storage properties (degradation, durability, etc.). Hence, there is still a need for detailed studies in the addition of binders in torrefied and densified biomasses, which will complement and enhance the results on binder addition presented in this research.

3.4. Production costs and potential revenue

Production costs for a 100,000 metric tons/year facility sum $199/metric ton, being a slightly higher value than that reported by Topell Energy [58]. Gonzalez et al. [24] found very similar production costs for torrefied wood pellets, assuming a 80,000 metric tons/year factory, with 199 $/metric ton[1]; sawmill co-products the biomass processed. Cerezo [81] reported values of $135/metric ton for torrefied wood only, which, considering the addition of pelletization processes, binders, etc., may represent a close value to the one reported here. This production cost is comparable to that reported by Pirraglia et al. [3] on regular wood pellets ($203.7/metric ton), indicating that torrefied wood pellets may be a competitor as profitable as regular wood pellets for co-firing applications. Current delivered price of coal for electric power sector, also known as steam coal (as of September 30th, 2011) is $144.44/short ton ($159.22/metric ton; U.S. Energy Information Administration, EIA [80]); at this cost

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[1] Converted from 2007 €/$ average rate, and transformed to 2011 dollar values with CWCCIS Index

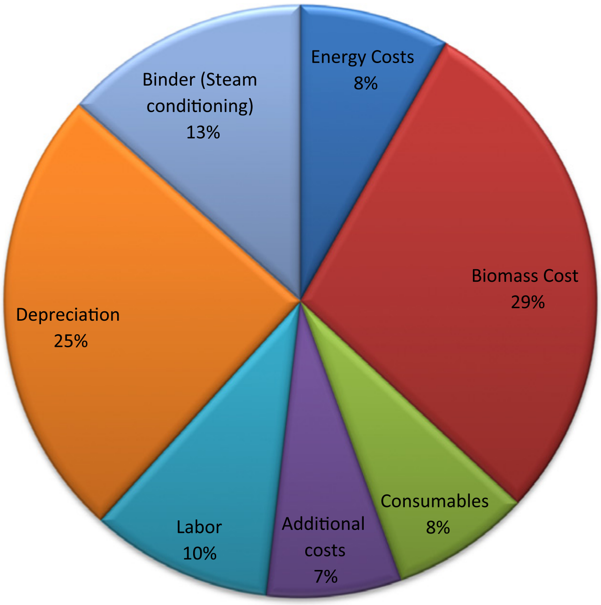

Fig. 5. Production costs distribution according to results from the model ($199/metric ton production costs).

of coal, torrefied wood pellets is still not competitive on a pure cost basis. However, regulations and mandates may influence the decision to utilize it in power plants beyond a cost analysis only.

The calculated production costs can be modified with add-in functions programmed in the income statement of the model, in order to adjust this cost to specific Internal Rates of Return (IRR), at a discount rate of 12% (also user modifiable variable), being able to obtain minimum revenue prices and Net Present Value (NPV) depending on a targeted IRR. Fig. 6 presents the adjustment of this price to different IRR's, and its effect in the NPV of the factory.

Current prices of regular "white" wood pellets vary depending on the producer, wood species, and region. In the current model, in order to obtain a break-even NPV (12% IRR, 12% discount rate), prices have to be greater than $261/metric ton. Compared to an average selling price of regular pellets of $280/metric ton [82], potential additional revenue of $19/metric ton can be achieved for producers considering this particular case. With additional transportation costs added following guidelines of Rhode [83] and Brechbill and Tyner [84], for maximum hauling distances of 80 km (truck delivery), final delivered costs may reach $282/metric ton ($21/metric ton for transportation, being $15/metric ton fixed cost and $0.12/metric ton/mile, plus $261/metric ton selling price), as this a slightly higher price than the average wood pellets price per metric ton. However, since torrefied wood pellets are still not a commercial fuel, it is yet to be estimated how much of a premium cost the potential market is willing to pay for such an upgraded product, and should be the subject of further investigations in this field.

3.5. Sensitivity analysis

The previously presented case study allows for further investigation in the profitability of a potential torrefied wood pellets plant, by observing how changes in the current values of the main variables for the model affect the NPV and minimum revenue of the facility. The changes tested and introduced in the values of CAPEX, Biomass, and other variables are ±25% of the current value evaluated in the model. Fig. 7 shows how changes in CAPEX and biomass delivered cost, affect minimum revenue at a 12% IRR.

The case of a torrefied wood pellets facility seems to be more affected by changes in CAPEX, than those produced by biomass delivered costs. As seen in Fig. 6, a change in ±25% in CAPEX has a deepened effect in the increase or decrease of the minimum revenue compared to that of biomass delivered cost. This case is opposite to that of regular wood pellets (as presented by [2]), in which biomass delivered cost is the most sensitive and influential variable in the profitability of a factory.

Changes in NPV and IRR when variables are modified can be seen in the next paragraphs. In the case of CAPEX, the NPV is affected reaching -$8069,694 and 10% IRR if costs increase. It will be positively influenced if capital costs are decreased (NPV = $11,861,433; IRR = 17%), which can be the case of further factories opening after the first successful ones are established, but only if the estimates of Bridgwater [69] on 20% CAPEX reduction on each doubling in the number of facilities are assumed as correct. Fig. 8 presents the information on IRR and NPV with changes in CAPEX.

Changes in biomass delivered cost represent the second most sensitive factor of the facility, affecting the IRR (11%) and NPV to −$3,113,905, while a decrease in the biomass delivered cost generates an increase in IRR to 14% and $6,849,679 of NPV. Fig. 9 demonstrates this effect.

Additional variables considered for this sensitivity analysis do not seem to have a substantial effect when compared to that of CAPEX and biomass delivered cost. The selection of an adequate binder, and a different technology in torrefaction, present some interesting results, due that these facts influence the CAPEX of the factory, by requiring either a conditioner and boiler unit (case of steam conditioning), or a set of biomass mixers (case of DDG, feed corn, and soybeans as binders), and due to the high capital cost of the current torrefaction technology selected (screw reactor). These analyses are presented next.

The selection of a different technology for the torrefaction process in the factory may have a considerable effect in the NPV and IRR, since this unit represents the majority of the capital costs of the facility. Fig. 10 shows the changes produced in NPV and IRR when selecting a different torrefaction technology.

Analyses from Fig. 10 indicate that if a technology such as rotating drum or moving bed reactor is implemented instead of the more traditional screw reactor, it might have a positive impact in the profitability of the business, subject to the condition that these alternative technologies become available and reliable at an affordable cost for the facilities. In order to obtain accurate estimates and compare more technological choices for the near future, it is recommended to further explore other torrefaction technologies and its potential associated engineering, maintenance, and repairs costs, as well as secure information on when the potential technologies could become available in commercial scale, Furthermore, a risk assessment of the technologies, suppliers, and potential for upgradability might complement this type of analysis and aid in decision making processes. Another important analysis for this type of facility is given by the binders utilized. In the case study, steam conditioning was assumed as the base case. However, changes in torrefaction parameters (medium and/or dark torrefaction) require the utilization of a different binder, thus producing changes in the amount of biomass required, amount of binder required, type of machines (mixers) utilized and capital costs associated. In Fig. 11, the effect of binders in the overall profitability is presented.

The selection of a different binder has varied effects in the profitability, when compared to the base case of steam conditioning. The selection of soybeans reduces the profitability of the business, due to its procurement cost and the proportion in which it must be used in the facility. This binder, with the current technology, is not recommended. The utilization of DDG and feed corn improves the IRR and NPV of the facility, being that feed corn is the best selection of binder. Further analyses are needed in order to observe if the

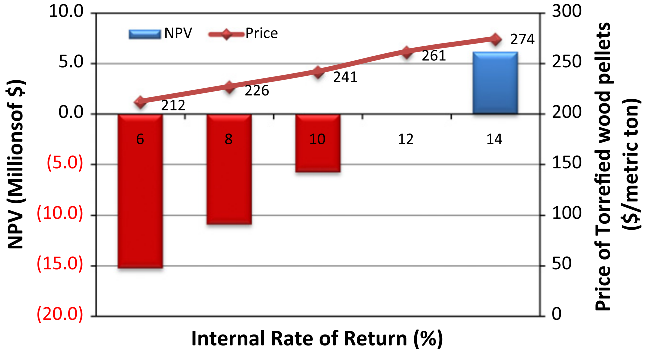

Fig. 6. Torrefied pellets price and NPV changes at different IRR.

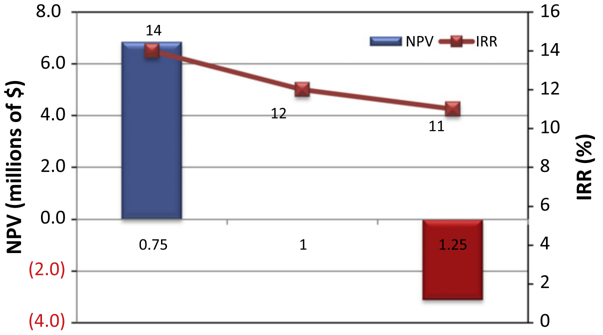

Fig. 9. Sensitivity of the model to changes in biomass delivered cost.

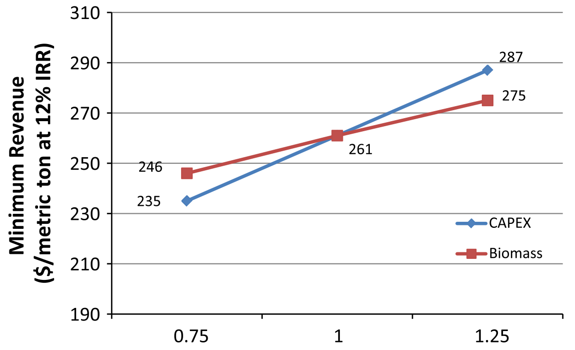

Fig. 7. Sensitivity of the minimum revenue to changes in CAPEX and biomass delivered cost.

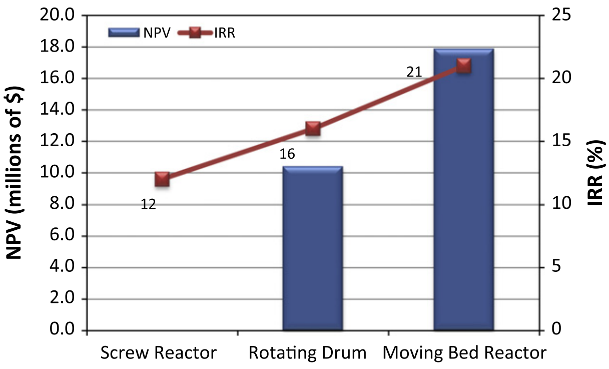

Fig. 10. Sensitivity of the model to changes in the torrefaction technology used.

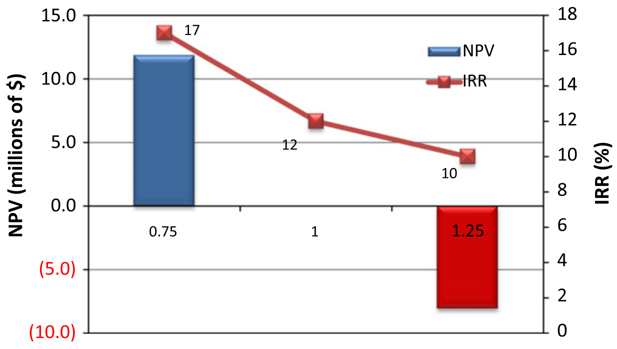

Fig. 8. Sensitivity of the model to changes in CAPEX.

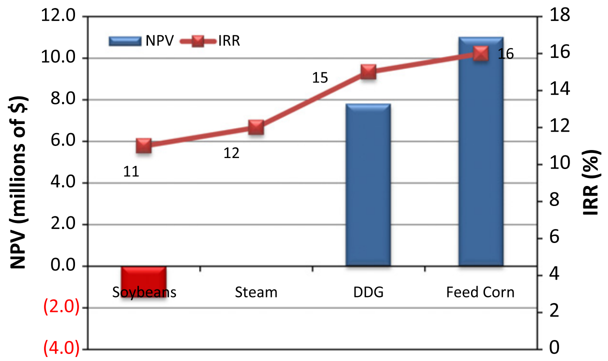

Fig. 11. Sensitivity of the model to changes in type and proportion of binder utilized.

addition (or change) of a binder have a negative effect on the HHV of the torrefied pellets; although previous work demonstrated that the addition of binders from seeds and grains do not have a significant reduction effect in the HHV of torrefied pellets [13]. It is important to highlight that depending on the technology utilized in the facility (torrefaction and pelletization in particular), it may become necessary to add steam conditioning even when utilizing soybeans or other binders, in order to enhance binding properties. Previous work performed by the authors has demonstrated that this step is not strictly required in order to form durable pellets [13]. The increase in durability, better flow of material through dies, and other properties when adding binder and steam conditioning requires further research in order to determine how necessary this step can be in large scale production.

An additional important variable introduced in the model is the utilization of carbon credits as an income source. In the base case scenario presented previously, all calculations were assumed with no carbon credits added. The addition of such income may significantly increase the likeability of a torrefied wood pellets facility. Childs [85] estimated that torrefaction companies in the US could benefit from carbon credits in a range between $36/metric ton to $72/metric ton of torrefied wood produced. Following these estimates, carbon credits income are considered in the model at a rate of $36/metric ton, and intermediate value of $52/metric ton, and a high value of $72/metric ton. Fig. 12 presents the changes produced in IRR and NPV of the facility when such scenarios are evaluated.

Fig. 12 indicates how the implementation of a carbon credits market may make the torrefied pellets business much more attractive. Considering the base case of $0/metric ton carbon credits, the increase in income from carbon credits may report an IRR of 17%, 20% and 22% respectively, while NPV can increase from $0 in the

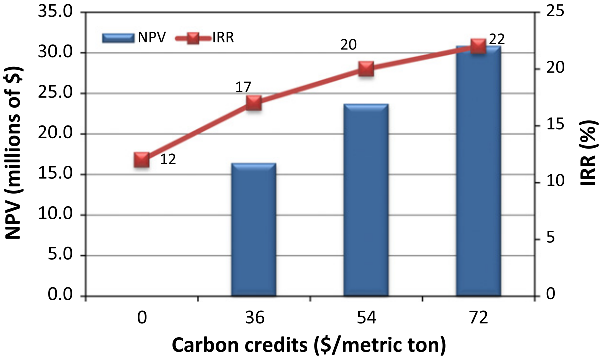

Fig. 12. Sensitivity of the project to different carbon credits scenarios.

base case, to more than $15 million on the lowest carbon credits estimate. Since the carbon credits market is still in its infancy in the US, caution is recommended when purely relying on these estimates. In the near future, it is possible that many companies may look to incorporate incomes from carbon credits, especially if the torrefied and pelletized material is intended for European markets. Europe has a more established regulation regarding carbon credits and bonuses for HHV delivered and carbon emissions reduction. These preliminary analyses indicate that carbon credits may be a key variable for this business in the short term, when analyzing its profitability.

As a final observation, further studies need to be developed in several areas to enhance and continue the work described in this research. Binder utilization and its effect on critical properties of torrefied and pelletized material, as well as types and quantities added needs to be developed. Torrefaction technology is another area that requires further attention. There are many different technologies being developed or near commercial stage. The evaluation of these technologies in the model, as well as having updated cost estimates for these technologies, will greatly enhance the accuracy of the estimates and provide more information for an accurate evaluation of profitability.

4. Conclusions

A dynamic, spreadsheet-based model was created[2] which allows evaluating technical and economic variables of a torrefied wood pellets facility in the US Results from the model and its sensitivity analysis indicate the following:

- The delivered costs of the biomass is the largest factor in the production costs of torrefied wood pellets, followed closely by the depreciation of the equipment, while energy consumption represents a small fraction on the production costs. The addition of a binder to this process also represents an important factor influencing production costs.
- When analyzing the sensitivity of the main variables that influence production costs, CAPEX represents the most sensitive variable, highly influencing the profitability of the facility (NPV and IRR); contrary to other options of biomass pre-treatment, such as wood pellets, in which biomass delivered cost represent the most sensitive variable. This is mainly due to the influence of the torrefaction unit in capital costs.
- The selection of a different torrefaction technology may have a significant influence in the CAPEX of the facility, thus further enhancing the profitability of the factory, subject to the capacity of the alternative technology to reduce overall capital costs, engineering, installation, and maintenance of the process, and subject to analysis of upgradability and risk.
- The selection of an adequate binder has a significant effect in the facility. The adequate selection of binder depending on torrefaction levels will allow improving and maintaining quality and consistency of the product. Additionally, selection of alternative types of binders may have an influence in the profitability of the business, since it modifies the equipment needs, capital costs, and proportion of binder to biomass utilized. In order to increase profitability and with the current evaluated conditions, DDG's and feed corn are recommended over soybeans.
- The back-calculated minimum revenue for a 100,000 metric tons/year facility for torrefied wood pellets is $261/metric ton. This is competitive revenue when compared to alternative pretreatments such as regular "white" pellets which have an average cost of $280/metric ton. With the addition of transportation costs, delivered price of torrefied wood pellets may reach $282/metric ton on power plants. Current biomass delivered options are similar in cost.
- A preliminary analysis of carbon credits as additional income in several different scenarios may considerably increase the likeability of the business, and further enhance profitability. More accurate scenarios must be described in order to obtain up-to-date values of potential carbon credit income per metric ton of product depending on delivered heating value of the torrefied pellets. This will allow for more accurate estimates of the increase in profitability of the facility with carbon credits in the United States.

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